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David B. Walker

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Georgia Institute of Technology
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- D. B. Walker, E. N. Glytsis, and T. K. Gaylord, "Electron wavepacket response of above-all-band-edges semiconductor quantum resonant structures," *J. Appl. Phys*, vol. 75, pp. 5415-5422, 15 May 1994.
- D. B. Walker, E. N. Glytsis, and T. K. Gaylord, "Ferroelectric liquid crystal wave-guide modulation based on switchable uniaxial-uniaxial interface," submitted for publication to *Applied Optics*.

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- David B. Walker
  School of Electrical and Computer Engineering
  Georgia Institute of Technology
  Atlanta, GA 30332

ABSTRACT

The research supported through the Fellowship consisted of three parts. The first was an investigation of the time dependent characteristics of above-all-band-edges resonant propagating structures. The second was an analysis of Ferroelectric Liquid Crystal waveguide modulators. The third was an study of lossless optical surface waves at the interface between anisotropic materials.

OUTLINE OF RESEARCH FINDINGS

The research sponsored by this contract consisted of three parts. The first part was a study of the time-dependent characteristics of above-all-band-edges resonant propagating semiconductor heterostructures. The second part was the analysis of ferroelectric liquid crystal (FLC) waveguide modulators using mode matching techniques. The third part was a study of surface polaritons in dielectrics using anisotropic crystals as the active material.

Time Response of Semiconductor Quantum Resonant Devices[1]

The time-dependent behavior of above-all-band-edges resonant propagating structures was studied. The results obtained were compared to those of the extensively studied double-barrier resonant structure for reference. It was found that for structures with the same resonant energies and resonance widths, the time-dependent characteristics are very similar. The structures were compared using two analytic approaches. The first is based on linear systems theory and the second on a finite difference time domain approach. It was found that for both structures, the quasibound state builds up at a rate determined by the parameters of the incident packet and decays with a time constant which corresponds to the lifetime.

Analysis of FLC Waveguide Switches[2]

Liquid Crystals have effective electro-optic coefficients orders of magnitude larger than other active integrated optic materials such as lithium niobate. However, previous studies of liquid crystal waveguides have mainly focused on nematic liquid crystals which exhibit impractically large scattering losses in a waveguide. Work with smectic liquid crystals and liquid crystals under strong confinement suggest the losses in these materials may be more manageable. In this study, the possibility of using FLCs in active waveguide modulators is explored through the analysis of several modulator configurations: a cutoff modulator, a deflection modulator, and an input coupler. To study these structures, a mode-matching technique was developed to analyze the effects of a step discontinuity in a uniaxial slave waveguide whose optic axis is in the plane of the waveguide. The analysis shows FLC modulators have many desirable performance characteristics and could form the basis for new practical waveguide modulators.

An FLC modulator is formed between two regions of differing optic axis orientations. Smectic C liquid crystals are binary; they may be placed in one of two orientations. Using the Smectic C liquid crystal in different orientations, different modulators can be produced.

The deflection modulator works by exploiting the fact that the direction of phase propagation and the direction of powerflow is different in anisotropic materials. By orienting the optic axis in complementary directions in the two regions, the input beam can be selectively displaced. When the deflection modulator was analyzed, it was found that the power transmission in the lowest order mode was 98.6%, and the deflection angle was 4.22°. This deflection angle is orders of magnitude larger than can be realized in well known materials such as Lithium Niobate.

The cutoff modulator operates by choosing the optic axis orientations so that in one state, guided modes are supported in the waveguide, and in the other all modes are cutoff. An important quantity for this type of modulator is the attenuation due to radiation losses in the cutoff waveguide. Because of the high birefringence of the FLC material it is expected that the attenuation be large. Analysis of the structure using the mode matching analysis shows very high attenuation in the cutoff waveguide, about 20dB/wavelength, and very little reflection from the abrupt interface.

The final problem is to devise a simple technique to launch a wave into the FLC waveguide. One possibility would be to initially launch a wave into an isotropic waveguide using standard launching techniques, then couple light into the FLC waveguide. To study the feasibility of this approach, the interface between an isotropic waveguide and FLC waveguide is analyzed using the mode matching technique. The transmission coefficient was found to be better than 95% and relatively insensitive to isotropic waveguide index. This suggests that this technique to launch light into the waveguide is feasible.

The high transmission of the deflection modulator and input coupler as well as the high attenuation of the cutoff modulator suggest that FLCs could be a practical technology for implementing waveguide modulators.

Surface Polaritons using Anisotropic Media

In 1988, D'yakonov discovered a new type of surface wave which propagates without loss at the interface between a positive uniaxial and isotropic material[3], and between two positive uniaxial materials[4]. In these studies, the optic axis was assumed to lie in the plane of the interface. These surface waves differ from other surface waves (polaritons) in that they do not depend on interactions with plasmons or phonons to activate the media. Instead, they are activated at visible optical frequencies. Due to the anisotropic nature of the materials, these modes propagate in only a small range of directions (defined as the acceptance angle). The greater the acceptance angle, the larger the confinement of the wave. The goal of this research was to produce results for arbitrary uniaxial and biaxial materials, and determine an experimental setup to verify the existence of these modes.

In order to devise an experiment to verify the existence of this mode, the materials chosen must

- produce a strong surface mode (large acceptance angle and confinement).
- be relatively insensitive to non-idealalities in the experiment.

The first case studied was a general uniaxial-isotropic interface where the optic axis is arbitrarily oriented. In this case, the transcendental equation defining the mode can be found analytically, and the mode found by root finding. It was found that any component of the optic axis in the plane normal to the surface of the interface produced a weaker surface mode.

The second case studied was a biaxial-isotropic interface where the optic axes in the biaxial material was in the plane or perpendicular to the plane of the interface. Again, an analytic expression for the mode dispersion can be found. For biaxial materials, the surface wave can always be found, though the mode is stronger in positive biaxial materials. When the optic axes are perpendicular to the interface, the strongest mode is found when propagating approximately midway between the two planar principal axes of the crystal. When the optic axes are in the plane of the interface, the strongest mode is achieved when propagating along a direction very close to the optic axis. In addition, the mode found is significantly stronger than for the mode where the optic axes are perpendicular to the plane of the interface.

The third case studied was a biaxial-isotropic interface where the principal axes of the biaxial crystal were arbitrarily oriented. Both the acceptance angle and confinement showed local maxima when the optic axes were oriented in the special cases described above and greatest effect when the optic axes are in the plane of the interface.

A major problem facing the experimental verification of these modes is the sensitivity of these structures to air gaps. It was found that an air gap 1/100th to 1/1000th of a wavelength thick between the active and inactive media was sufficient to inhibit the surface wave. Clearly, the two materials must be intimately joined to observe this mode.

The device configuration chosen to verify the surface modes is y-cut KTP with a liquid cover. The liquid cover was chosen to achieve the tight bonding along the interface. Light will be coupled in by end-firing. This setup gives the best chance of observing these modes.

Bibliography

[1] D. B. Walker, E. N. Glytsis, and T. K. Gaylord, "Electron wavepacket response of above-all-band-edges semiconductor quantum resonant structures," *J. Appl. Phys*, vol. 75, pp. 5415-5422, 15 May 1994.

[2] D. B. Walker, E. N. Glytsis, and T. K. Gaylord, "Ferroelectric liquid crystal waveguide modulation based on switchable uniaxial-uniaxial interface," submitted for publication to *Applied Optics*.

3 M. I. D'yakonov, "New type of electromagnetic wave propagating at an interface," *Sov. Phys. JETP*, vol. 67, pp. 714–716, April 1988.

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